ON THE CTBT MONITORING POTENTIAL OF USING LG-PHASE ARRIVAL TIMES AT LOCAL AND REGIONAL DISTANCE RANGES

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ABSTRACT

The prominent Lg wave is nearly always observed at local and regional distances. It is a surface wave propagating with almost constant group velocity around 3.5 km/s over a vast distance range of hundreds to thousands of kilometers. Thus, Lg propagation should in principle simplify epicenter location schemes, based on relative travel time equations. In our ongoing efforts to accomplish this we computed Hilbert or STA-envelopes and showed that in many recordings from Fennoscandia and Central Europe the Lg group velocities measured using the envelope peak arrival times are remarkably consistent. However, they tightly concentrate around 3.4 km/sec for the Baltic shield of Fennoscandia and around 3.2 km/sec for the much younger crust of Central Europe. These Lg picks were subsequently used in the Pinsky (2008) relative time location algorithms of "group beamforming" and "probabilistic beamforming" for refined epicenter locations in Balticum.

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OBJECTIVES

An often prominent phase arrival in local and regional seismic event recordings is the Lg-wave which propagates in the crustal wave guide. It was first reported in the seismological literature in 1952 by Press and Ewing. Analysis of Lg-records is popular for both ML-magnitude estimation and mapping attenuation (the Q-parameter) in the crust. Another obvious application of Lg-phase arrivals would be enhanced epicenter locations in view of the relatively high signal frequency of this phase and its slow propagation velocity at 3.5 km/sec.

To improve event locations we need mapping of the 3D velocity structure of the Earth and to collect so-called ground truth (GT) events for testing the adequacies of such approaches. Such models and GT-events are at present only available for limited areas. Hence, applying erroneous velocity models may result in biased epicenter solutions and, thus a remedy to avoid complicated 3D velocity models is an attractive challenge. Our approach here is for so-called model independent location schemes using a model of relative travel times and assuming homogeneous or simple 1D velocity environments for station clusters. An approach that is similar in principle to generalized beamforming has been introduced by Kværna and Ringdal (1996) for real-time seismic monitoring. These methods are attractive as they seemingly minimize velocity uncertainties in the Earth's interior but such uncertainties may penetrate into velocity models when we increase sizes of networks and cluster array apertures. In the scheme used in this study such uncertainty measures are incorporated in the final epicenter estimates (Pinsky, 2008). Below we briefly sketch the actual location approaches used.

RESEARCH ACCOMPLISHED

1. Epicenter Location Method

Let us introduce "pseudo-slowness" $\boldsymbol{\beta}$ as a coefficient between the travel time difference $\boldsymbol{\tau_k - \tau_j}$ of a given seismic phase (P, S or Lg) for a pair of stations $\boldsymbol{Y}_k$ and $\boldsymbol{Y}_j$ and distance $\boldsymbol{R}$ difference $\boldsymbol{D_{kj}}$ from a given point (source) X on the Earth's surface. Then $\boldsymbol{D_{kj}}(X)=\boldsymbol{R_k(X) - R_j(X)}$ and we get the travel time difference equation:

$$[\,\tau(X,Y_k) - \tau(X,Y_j)\,] = \beta D_{kj}(X). \qquad (1)$$

Then a travel-time equation for the pair of stations looks like:

$$t_k - t_j - [\,\tau(X,Y_k) - \tau(X,Y_j)\,] = t_k - t_j - \beta D_{kj} = \varepsilon_{kj}(X). \qquad (2)$$

Equation 2 constitutes a "theoretical" stage of knowledge about arrival time differences $t_k - t_j$ in terms of Tarantola (2005). Measuring uncertainty $\boldsymbol{\varepsilon_{kj}}$ using a bell-shape "theoretical" function Ω (Pinsky, 2008), the robust location procedure yields in maximizing a probability density function (PDF) of the shape

$$F(X) = \sum w_{kj}\,\Omega(\varepsilon_{kj}(X)/\sigma), \qquad (3)$$

where σ is a scaling coefficient, w_{kj} is a weighting factor, and $\boldsymbol{X}$ is the unknown source. As an example of the bell-shape function Ω one may use the Gaussian: $\exp(-x^2/2)$ as in (Lomax, 2005) or a cosine function: $\cos(x)$, $(-\pi < x < \pi)$ as in (Pinsky, 2006).

From Equation 3 and using the notion of "pseudo-slowness" we get two location schemes avoiding previously known deterministic travel time models $\boldsymbol{\tau}$, namely the "group beamforming" and "probabilistic beamforming."

1-A. *Group Beamforming.*

Group Beamforming (GB) is based on splitting a network into M sub-networks W_m ,m=1,… M in which the pseudo-slowness $\boldsymbol{\beta} = b_m$ is a constant, when both stations of the pair belong to W_m. GB is achieved by jointly maximizing F(X)=F(X,B) in Equation 3 relative source coordinates $\boldsymbol{X}$ and the vector of pseudo-slowness values: $\boldsymbol{B}=\{b_1, b_2,\ldots, b_M\}^T$. For this purpose we are using direct grid-search over parameters $\boldsymbol{X}$ and $\boldsymbol{B}$. Because model parameters $\boldsymbol{B}$ are found jointly with event coordinates $\boldsymbol{X}$, the algorithm doesn't require a priori exact knowledge of the Earth model. If parameter vector $\boldsymbol{B}$ is considered known a priori from some Earth model or observations it will serve a role of parameter in PDF of $\boldsymbol{X}$ described by Equation 3. GB location fits well to the concept of Lg-waves energy propagation with constant velocity at large distance ranges. For example, let us presume that our Lg picks for Event #4 are subdivided in two groups of stations: one in Fennoscandina and another in Continental Europe having different average velocities of 3.2 km/s and 3.4 km/s, respectively. Application of the GB in such a case is

straightforward. We may also use the scheme with two constant pseudo-slowness parameters: 1/3.2 and 1/3.4 respectively.

1-B. *Probabilistic Beamforming.*

Assume uncertainty of pseudo-slowness is described by the pdf ***f(x)*** for all station pairs. Then Equation 3 transforms into probabilistic beamforming (PB) scheme :

$$F(X) = \sum w_{kj} \int f(x)\Omega\{[t_k - t_j - xD_{kj}(X)]/\sigma\}dx \qquad (4)$$

Pinsky (2008) considers several variants of the PB formulation above. Here we shall limit ourselves to the case when the pseudo-slowness $\boldsymbol{\beta}$ is equally distributed in the interval (β_1, β_2) and does not take values outside this interval. Then the PDF of the source location Eq. (3) becomes:

$$F(X) = \sum_{k,j} w_{kj} \int_{b_1}^{b_2} \Omega[(t_j - t_k - xD_{kj})/\sigma]dx \qquad (5)$$

For Gausian ‘’theoretical" function Ω (x) = exp(-x^2/2) eq. (4) will transform to

$$F(X) = \sum_{k,j} \frac{w_{kj}}{D_{kj}} (F_N[(t_j - t_k - \beta_1 D_{kj})/\sigma] - F_N[(t_j - t_k - \beta_2 D_{kj})/\sigma]) \qquad (6)$$

where *FN(x)* is a standard normal probability distribution function. For the cosine “theoretical” function ***Ω (x)*** = cos(***x***) eq.(4) will transform to:

$$F(X) = \sum_{k,j} \frac{w_{kj}}{D_{kj}} [\sin(D_{kj}(\beta_2 - \beta_1)/2)\cos(t_j - t_k - D_{kj}(\beta_1 + \beta_2)/2)] \qquad (7)$$

Choosing GB or PB depends on the case under consideration. The hybrid GB/PB schemes, when different PDFs are used for different station groups, are also practical. However, splitting the network might not be advantageous, because this way we reduce essentially the number of pairs and weaken constraints provided by the station pairs on the "opposite" sides of the epicenter. Hence, for using GB we need a good argument for splitting the network. In Pinsky (2008) for accurate location of nuclear tests the PB was used, because background experiments showed it to be more accurate. Choosing the pseudo-slowness range (β_1, β_2) depends on the range of epicenter-station distances. For example, if only regional+ local stations are involved, then for the P phase the range should not exceed 1/8.5 s/km from above and 1/6 s/km from beneath. Below we shall provide PB locations for four Baltic events using bulletin P arrivals and GB for event #4 using Lg picks.

2. Lg-Feature Extraction from Waveform Data

A prominent feature in SP seismograms at local and regional distances is the Lg-wave, which arrives well behind the Sn-wave train. Among the first to report on such observations were Press and Ewing (1952), who interpreted it as a surface shear wave propagating in the crustal wave guide. Their study triggered many investigations aiming at better understanding of Lg-wave propagation, amplitude decay with distance, crustal Q and so forth (e.g., see Nuttli, 1973; Campillo, 1990; Hansen et al., 1990; Mendi et al., 1994; Fedorenko et al., 1999; and Husebye et al., 2002). Despite the many efforts in modelling and understanding Lg-propagation, the practical usages of this `phase' are little explored. In particular the T=R/3.5+3.5 travel time line for the peak of energy propagation at regional distances may be used for robust epicenter locations as a supplement to the P arrival times in the envelope based location scheme by Pinsky, (2000). Also Husebye et al. (1998) reported Lg-phase arrival times in a consistent manner. From mode theory we have that the first and the next higher Lg-modes in the frequency range of 0.5 - 2.0 Hz have velocity minima at 3.40 +/- 0.10 km/sec so we intuitively expect that the energetic part (or peak amplitude) of the Lg-wave will travel with a group velocity around 3.40 km/sec as actually observed (Panza and Calcagnile, 1974 and Mykkeltveit and Husebye,1981). In short, we will attempt to measure the Lg-phase arrival time at its peak amplitude in the envelope of the original waveform record. The envelope formation from the original waveforms are a smoothing operation and hence peak amplitude pickings can hopefully be made consistently which is otherwise not feasible using the original waveform records.

The first task here is that of checking whether a signal is present or not. This is achieved through a signal detector operation of the form STA/LTA > TH where STA is a short-term average (e.g., a root mean square [RMS] trace

power estimate) and LTA is the long term average defined in a similar manner. The threshold TH is given a value around 4.0 thus ensuring a moderate false alarm rate (Fedorenko et al., 2008). Anyway, the STA-operation transforms the original, pre-filtered waveform trace into a smooth envelope trace (a simplified form of the Hilbert transform operation) and will always be available as part of the signal detection operation. Our idea is to relate Lg-arrival time picks to the envelope peak amplitudes in the STA-envelopes usually identical to each other. After pre-filtering the original traces in a signal bandwidth around 0.5–2.0 Hz and resampling with a rate as low as 2 s/sec so we interpolate for picking times at the nearest 10th of a second. This is a simple and easy waveform operation to perform even in near real time. After experimenting with different envelopes and parameter settings we choose the STA-window length equal to 2.0 sec and updating every 0.5 sec for smoothing operation (example in Figure 1). For Lg-waves it is unclear whether their origin time is focal-depth dependent—at best weakly in view of their 'multiple reflections' generation mechanism. In the epicenter location schemes outlined above, we treat P- and Lg-arrival times independently thus avoiding this possible bias. It remains to demonstrate that introducing invariant and possibly focal depth independent Lg-phase travel times we may obtain enhanced source locations. We try to answer these questions through reanalysis of 4 Baltic region earthquakes. Regrettably, we have only Lg-recordings for the second Kaliningrad earthquake of 21 September 2004, which have been studied in detail by Husebye and Mantyenemi (2005) and Gregersen et al. (2007). Seemingly, up to 2005, only waveforms sampled at 1 s/sec were stored by IRIS and ORFEUS and similar agencies.

3. Events used in the Baltic Location Experiment

The four events used in the analysis are listed in Table 1 and are to our knowledge the largest earthquakes in the Baltic region since 1950. The two most recent ones took place close to the Russian city Kaliningrad (formerly Kønigsberg) in 2004, and despite a moderate magnitude of 5.0, caused considerably local damages (Gregersen et al, 2007; Husebye and Mantyenemi, 2005). These two earthquakes are of particular interest because 1) there was some dispute on exact epicenter location among the authors of the Gregersen et al. paper and 2) an abundance of digital records were available from many stations within a distance range of 2000 km for Event #4 (see Figure 2). The latter makes it feasible to test the relative merits of including Lg-readings in the epicenter location process. A puzzling feature here is that the two Kaliningrad earthquakes are often given nearly the same magnitude value, but the first one hardly produced any Lg-recordings.

The earthquake off-coast of Estonia was given much attention in 1976 as some newspapers suggested that this was an accidental nuclear explosion (Slunga, 1979). The one in 2002 to the south of Gotland (earthquake or explosion undecided), is also relatively strong ensuring many station reports but again hardly any digital records available. For the four events analysed, we have accepted P-arrival time readings as they appear in the International Seismological Centre (ISC) bulletins. The Swedish network readings were obtained from the local bulletin, Seismological Laboratory, Uppsala University. For the 1976 event, no waveform records were available but a relocation experiment using a better travel-time table and a different location scheme may be interesting. The same applies to Events #2 and #3 because no Lg-recordings were available. As mentioned, Event #4 is the exception with many Lg-recordings and corresponding Lg arrival-time data. This event is also by far the most interesting because, as far as we know, we are among the first to attempt using Lg-times in estimating the epicenter location for an earthquake.

4. Epicenter Relocation of Four Baltic Events using the Model-Free PB Method

First we used P picks from the ISC bulletins to relocate four Baltic events using the probabilistic beamforming scheme in the form of Equation 7. The parameters used for the location are: $\beta 1 = 1/100$ s/km, $\beta 2 = 1/7.5$ s/km, $\sigma = 2.5$ s.

The results of location are summarized in the Table 1. The Error column denotes the geometrical average of the two axes of the error ellipsoid estimated in the ISC, which appear to be too optimistic, because the scatter of epicenter location by different agencies essentially exceeds the error value. For example, for Event #4, the latitude varies from 54.7˚ to 55.04˚ and longitude varies from 19.08˚ to 20.19˚ (Gregersen et al., 2007). Besides, the two Kalinigrad events are most probably collocated; however, the distance between the ISC epicenter determinations is equal to 5 km. In this sense our PB locations, though falling out of the confidence area possess somewhat intermediate reasonable values.

5. Lg picking for Event N4

We took Lg picks obtained from the waveforms of Event N4 recorded at N=16+26+9=51 stations located in Europe, Scandinavia, and Finland, respectively (see Figure 2). The picks are presented in Figure 3 together with the travel-time curves. Occasionally, we picked STA-maxima (outliers) for the Sn-phase, but this is easily controlled by requiring the maximum reading to be within the 3.1–3.6 km/sec velocity window. Lg travel times are obtained as the differences between arrival times and the source origin time. Tables 2 and 3 document Lg pick velocities using location and origin time obtained by ISC and demonstrate together with the Figure 3 data, amazing stability of the velocity within different sub-networks. However, Lg velocities to the South of the Epicenter (Table 3) and to the North (Table 4) differ consistently and close to the mean values V=3.21 and V=3.38 km/s, respectively. The mean value difference of 0.17 km/s exceeds two standard deviations 2σ=0.16 km/s between them. The discrepancy is apparently seen also in Figure 3. Several outliers are also observed, such as at station KIF, which is 1,582 km away. Special effort to remove outliers for the best Lg velocity estimation is reflected in the tables.

Table 1: Earthquakes in the low-seismicity area Baltic subjected to relocations using PB

Event	Date y/m/d	O.Time (h/m/s)	Latitude	Longitude	Error km	Deviation km	Nsta	Ml	Algorithm (Agency)
1	1976/10/25	08/39/44.69	59.2030˚	23.5818˚	6.4	6.95	70	4.4	ISC
			59.2600˚	23.5800˚			70		PB
2	2002/12/18	21/14.15.68	56.0585˚	18.0511˚	5.1	14.6	58		ISC
			55.9324˚	18.0110˚			58		PB
3	2004/09/21	11/05/03.00	54.8300˚	20.0400˚	2.34	5.8	544		ISC
			54.8700˚	20.0900˚			242		PB
4	2004/09/21	13/32/28.51	54.8254˚	19.9740˚	2.25	7.6	380		ISC
			54.8854˚	20.0340˚			380		PB

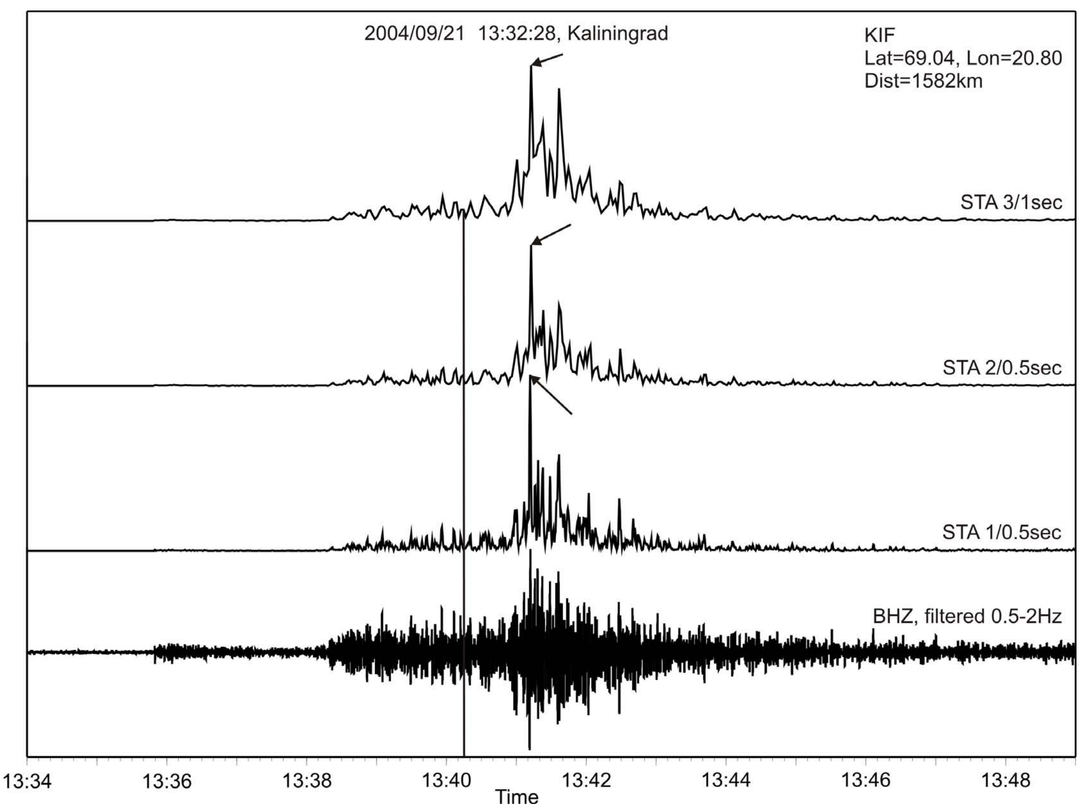


Figure 1. STA maximum amplitude picking (Lg pick) for various STA shows to be independent of smoothing window parameters (duration/shift) at station KIF. However, the Lg pick is anomalously late here (see also outlier point in Figure 3 at a distance of 1,582 km). The vertical line is the expected arrival time for the Lg phase in assumption that Lg velocity is 3.4 km/s.

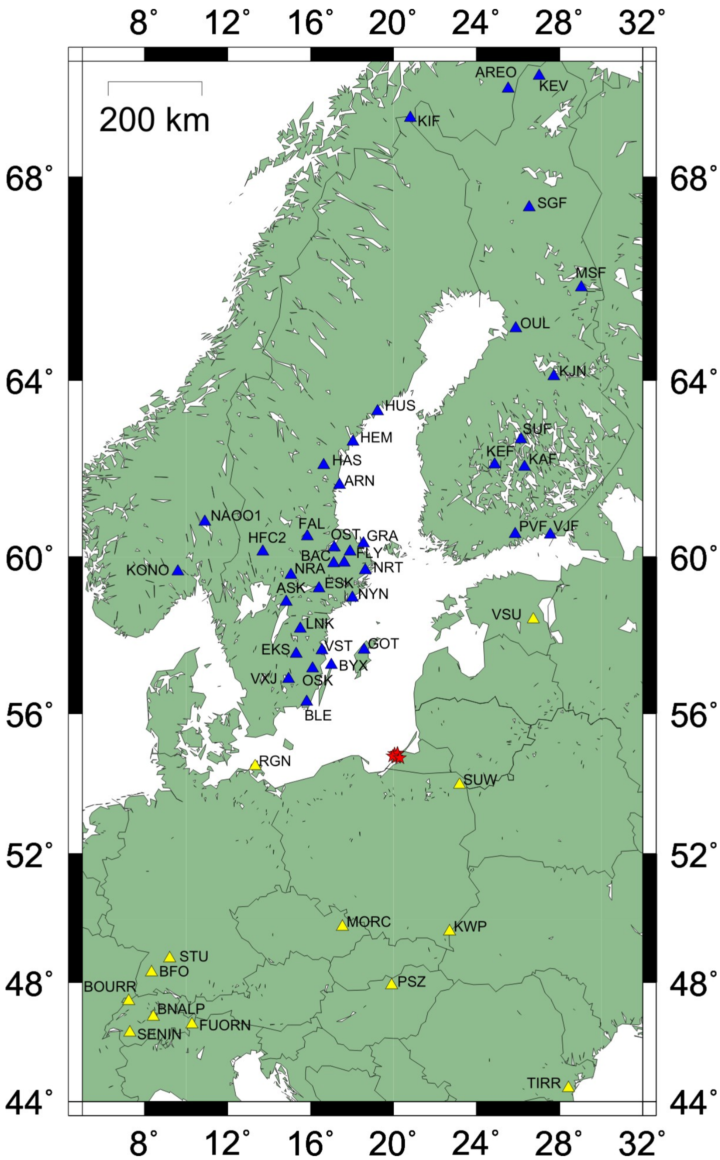


Figure2. Scandinavian (SCAN), Finland (FIN) and Continental (EUR) group of stations ▲ used for Lg pickings of event #4. The set of stars depict different locations of the event.

6. Model-Free PB and GB Relocations of Event N4 using Lg Picks

The relocations using Lg picks are summarized in Table 4, where PB of Equation 7 and GB with cosine target function $\Omega = \cos(x)$, $(-\pi < x < \pi)$ are applied for different network configurations comprised of EUR, SCAN, and FIN networks. For PB we have taken the pseudo-slowness interval determined by $V1 = 1/\beta 2 = 2.5$ km/s, $V2 = 1/\beta 1 =$ 4.2 km/s and the scatter parameter $\sigma = 4$ s. For GB velocity, the lower limit was determined as $V1 = 1/\beta 2 = 2.5$ km/s and was changed incrementally in a grid-search with the step dV=0.1 km/s, NV=15, $\sigma = 4$ s.

The latitude-longitude grid was 0.4˚X0.4˚ with a 0.02˚ interval. The locations obtained by GB in EUR+SCAN+FIN and EUR alone deviate from the ISC reference Lat=54.8254˚ Long=19.9740˚ by 8.5 and 11 km respectively, thus remaining within the latitude-longitude intervals given by epicenter locations from different agencies using P arrivals in the ISC bulletin (see above). As the result of the grid-search we get the pseudo-apparent

Lg velocity for each of the sub-networks as 3.1, 3.5, and 3.5 km/s, respectively at the maximum of the PDF (see Figure 4). These velocities slightly differ from the 3.2, 3.38, and 3.40 km/s velocities obtained as the result of the direct Lg group velocity computation. Using the Gaussian target function $\Omega = \exp(-x2/2)$ provided a close and similar result.

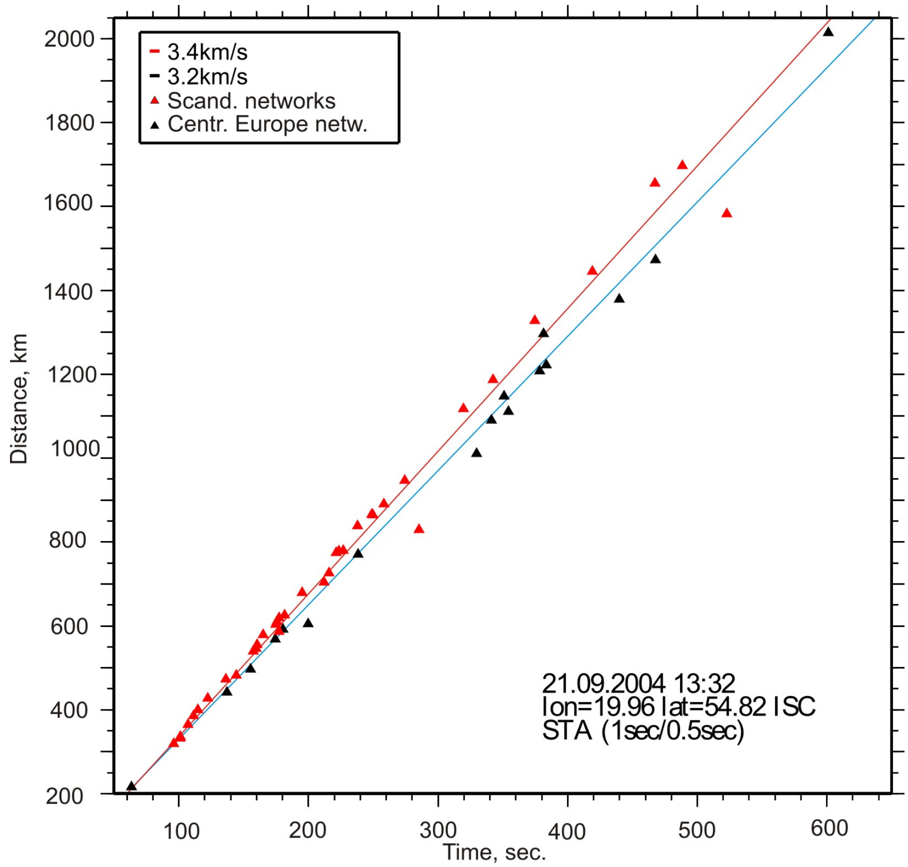


Figure 3. Lg picks and the corresponding travel-time lines determined from the Fennoscandia and Central Europe groups of stations. The ISC epicentre location and origin time of the Event #4 are taken as reference for the travel time and distance calculations.

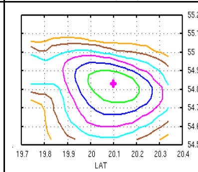
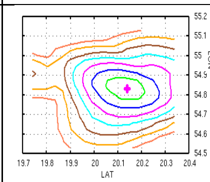
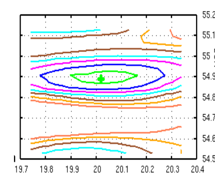
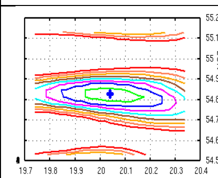
Table 2. Mean Lg group velocities and standard deviations relative to locations by different agencies for stations South to Epicenter. * notes that calculations were made excluding the outliers with velocities (for SUW and TIRR > 3.4 km/sec, for KWP and STU < 3.1 km/sec,)

Agency	Mean Velocity, km/sec	Std. deviation km/sec	Mean Velocity*, km/sec	Std. deviation* km/sec
IGF IASP	3.23	0.12	3.23	0.07
IGF AK	3.24	0.11	3.23	0.07
EMSC	3.22	0.10	3.22	0.06
ORFEUS	3.17	0.14	3.15	0.09
NEIC	3.20	0.15	3.18	0.09
ASS	3.21	0.12	3.20	0.07
GSRAS	3.21	0.10	3.21	0.06
MOS	3.19	0.09	3.19	0.06
ISC	3.17	0.13	3.16	0.08
IGF	3.22	0.11	3.21	0.06
Mean Instrumental	3.21	0.11	3.20	0.07

Table 3. Mean Lg phase velocities and standard deviations relative to locations by different agencies for stations North to Epicenter. * notes that calculations were made excluding the outliers with velocities (for KONO < 3.0 km/sec, AREO > 3.5 km/sec)

Agency	Mean Velocity, km/sec	Std. deviation km/sec	Mean Velocity*, km/sec	Std. deviation* km/sec
IGF IASP	3.48	0.13	3.50	0.06
IGF AK	3.41	0.12	3.42	0.07
EMSC	3.36	0.12	3.38	0.08
ORFEUS	3.33	0.14	3.34	0.09
NEIC	3.34	0.13	3.36	0.09
ASS	3.35	0.13	3.36	0.08
GSRAS	3.40	0.12	3.42	0.07
MOS	3.30	0.12	3.32	0.08
ISC	3.32	0.13	3.33	0.09
IGF	3.36	0.13	3.38	0.08
Mean Instrumental	3.37	0.13	3.38	0.08

Table 4: **Relocation of Earthquake N4 using Lg picks, PB and GB algorithms**

Algorithm	Network	Lat	Lon	V_{EUR}	V_{SCAN}	V_{FIN}	PDF F(X)
GB	EUR+SCAN+FIN	54.83˚	20.1˚	3.1	3.5	3.5	
GB	EUR	54.83˚	20.14˚	3.1			
PB	EUR+SCAN	54.89˚	20.02˚				
PB	EUR	54.83˚	20.04˚				

The epicenters given by PB are closer to the ISC solution, deviating by 8.5 and 4.4 km from the reference location, though the PDF patterns look worse due to the close local maxima and the elongated E-W shape. Note that using EUR stations alone provide better results, probably because of problematic association of stations from the different sub-networks. The SCAN and FIN networks alone or together are not useful for the epicenter location due to the poor azimuth constrain they provide.

CONCLUSIONS AND RECOMMENDATIONS

The idea of this small chamber study was testing some alternative methods of earthquake location using a set of four interesting events, which occurred in Baltic region. On the other hand it was intriguing to verify how linearity of travel time of the Lg energy peak propagation would contribute to the earthquake location. There was only one event, the second Kaliningrad earthquake in the set, from which the Lg arrival times could be picked from the waveforms. However, even in this modest effort we obtained some interesting results.

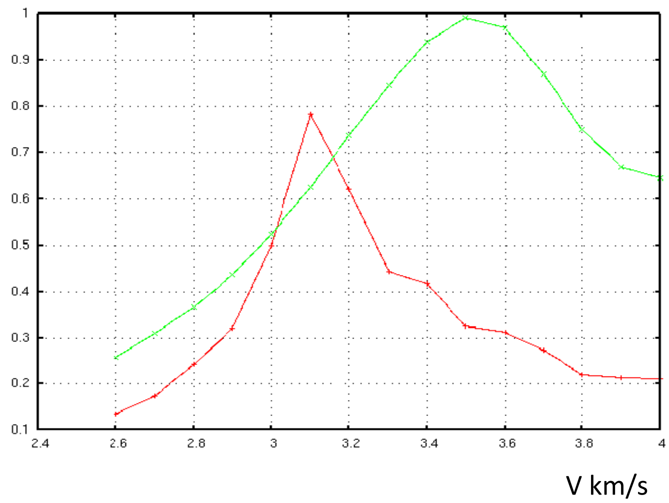


Figure 4. Probability density distribution functions F(X,B) of apparent velocities for the EUR (red) and SCAN (green) groups of stations respectively. The epicenter X: Lat=54.83˚ Lon=20.1˚ is fixed.

For epicenter location we have chosen the model-free robust GB and PB methods of Pinsky (2008), who demonstrated their effectiveness for a large set of nuclear test locations in regional and teleseismic distance ranges. The so-called pseudo-slowness notion introduced in PB and GB helps to accommodate uncertainties of velocity model when an explicit 3D model is not available. Therefore, we assumed that these methods might be helpful in large-scale heterogeneous conditions observed in the Baltic area. Besides, these relative time location methods are best suited for the case of travel times close to linear, as demonstrated by the Lg phase for Event #4. As the result of application of the PB to the P arrivals reported in the ISC bulletin for the four events we got epicentre locations which are reasonable and comparable to the reports of different agencies, yet out of the confidence area determined from the too optimistic Gaussian assumption.

Analysis of the Lg energy propagation revealed two apparent linear branches of the travel times as determined by more than 50 picks of the event: one for the continental stations with velocity V=3.2±0.07 km/s and the other for Scandinavian shield (Sweden and Finland) with V=3.38±0.08 km/s. Hence, the GB application, based on splitting the network into several sub-networks was straightforward as applied to the Lg picks and showed satisfactory results. The pseudo-apparent velocities determined independently as the result of the grid-search appeared rather close to those from the direct computation mentioned. The PB was applied to the Lg picks either and though the results are closer to those of the ISC, the solution looks less stable, because the assumption used about the even distribution of the pseudo-slowness is violated in this case. Note that the ISC epicentre location used as a reference is not a ground truth. Moreover, it gives almost one σ less Lg velocity than the average for velocity data from both Fennoscandian and Central European networks.

For complimenting the study we plan and recommend to 1) increase the waveform data set by available events; 2) elaborate on methods for jointly using P picks with the Lg picks for enhanced location; 3) consider hybrid PBGB methods; and 4) provide 3D modelling of travel times for events under consideration and the corresponding location experiments.

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